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On the Alternatives of Lyapunov's Direct Method in Adaptive Control Design

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Abstract

The prevailing methodology in designing adaptive controllers for strongly nonlinear systems is based on Lyapunov's PhD Thesis he defended in 1892 to study the stability of motion of systems for the solution of the equations of motion of which no closed form analytical solutions exist. The adaptive robot controllers developed in the nineties of the 20thcentury guarantee global (often asymptotic) stability of the controlled system by using his ingenious Direct Method that introduces a Lyapunov function for the behavior of which relatively simple numerical limitations have to be proved. Though for various problem classes typical Lyapunov function candidates are available, the application of this method requires far more knowledge than the implementation of some algorithm. Besides requiring creative designer's abilities, it often requires too much because it works with satisfactory conditionsinstead of necessary and satisfactoryones. To evade these difficulties, based on the firm mathematical background of constructing convergent iterative sequences by contractive maps in Banach spaces, an alternative of Lyapunov's technique was so introduced for digital controllers in 2008 that during one control cycle only one step of the required iteration was done. Besides its simplicity the main advantage of this approach was the possible evasion of complete state estimation that normally is required in the Lyapunov function-based design. Though the convergence of the control sequence can be guaranteed only within a bounded basin, this approach seems to have considerable advantages. In the paper the current state of the art of this approach is briefly summarized.

Keywords: Adaptive control; Lyapunov function; Banach space; Fixed point lteration

Abbreviations: AC: Adaptive Control; AFC: Acceleration Feedback Controller; AID: Adaptive Inverse Dynamics Controller; CTC: Computed Torque Control; FPI: Fixed Point Iteration; MRAC: Model Reference Adaptive Control; OC: Optimal Control; PID:Proportional, Integrated, Derivative; RARC: Resolved Acceleration Rate Control; RHC: Receding Horizon Controller;SLAC: Slotine-Li Adaptive Controller;

Introduction

There is a wide class of model-based control approaches in which the available approximate dynamic model of the system to be controlled is "directly used" without "being inserted" into the mathematical framework of "Optimal Control" (OC). A classical example is the "Computed Torque Control" (CTC) for robots [1]. However, in the practice we have to cope with the problem of the imprecision (very often incompleteness) of the available system models (in robotics e.g. [1,2], modeling friction phenomena e.g. [3-7], in life sciences as modeling the glucose-insulin dynamics e.g. [8-11] or in anesthesia control e.g. [12-14]). Modeling such engines as aircraft turbojet motors is a quite complicated task that may need multiple model approach [15-18]. Further practical problem is the existence and the consequences of unknown and unpredictable "external disturbances". A possible way of coping with these practical difficulties is designing "Adaptive Controllers" (AC) that somehow are able to observe and correct at least the effects of the modeling imprecisions by "learning". Depending on the above available information on the model various adaptive methods can be elaborated. If we have precise information on the kinematics of a robot and only approximate information is available on the mass distribution of a robot arm made of rigid links the exact model parameters can be learned as in the case of the "Adaptive Inverse Dynamics" (AID) and the "Slotine-Li Adaptive Controller" (SLAC) for robots that are the direct adaptive extensions of the CTC control. An alternative approach is the adaptive modification of the feedback gains or terms [19]. The "Model Reference Adaptive Control" (MRAC) has double "intent": a) it has to provide precise trajectory tracking, and b) for an outer, kinematics-based control loop they have to provide an illusion that instead of the actually controlled system, a so called "reference system" is under control (e.g. [20-22]).

The traditional approaches in controller design for strongly nonlinear systems are based on the PhD thesis by Lyapunov [23] that later was translated to Western languages (e.g. [24]). (In this context "strong nonlinearity" means that the use of a "linearized system model" in the vicinity of some "working point" is not satisfactory for practical use.) In Lyapunov's "2nd" or "Direct Method" a Lyapunov function has to be constructed for the given particular problem (typical "candidates" are available for typical "problem classes"), and non-positiveness of the time-derivative of this function has to be proved. Besides the fact that the creation of the Lyapunov function is not a simple application of some algorithm –it is rather some creative art–, this method has various drawbacks as a) it works with "satisfactory conditions" instead of "necessary and satisfactory conditions" (i.e. often it requires too much as guaranteeing really not necessary conditions), b) its main emphasis is on global (asymptotic) stability of the motion of the controlled system without paying too much attention to the "initial" or "transient" phase of the controlled motion (for instance in life sciences a "transient" fluctuation can be lethal).

To cope with these difficulties alternatives of the Lyapunov function-based adaptive design were suggested in [25] in which the primary design intent is keeping at bay the initial "transients" by turning the task of finding the necessary control signal to iteratively so solving a fixed point problem ["Fixed Point Iteration" (FPI)] that in each digital control step only one step of the appropriate iteration can be realized. The mathematical antecedents of this approach were established in the 17th century (e.g. [26-28]), and its foundations in 1922 were extended to quite complicated spaces by Stefan Banach [29,30]. In [25] the novelty was the application of this approach to control problems. In contrast to the "traditional" "Resolved Acceleration Rate Control" (RARC) in which in the control of a 2nd order physical system only lower order derivatives or tracking error integrals are fed back (e.g. [19,31-33]) in this approach the measured "acceleration" signals are also used as in the "Acceleration Feedback Controllers" (AFC) (e.g. [34-38]).

In general, the most important "weak point" of the FPI-based approach is that it cannot guarantee global stability. The generated iterative control sequences converge to the solution of the control task only within a bounded basin that in principle can be left. To avoid this problem heuristic tuning rules were introduced for one of the little numbers of the adaptive parameters in [39-41]. In [42] essentially the same method was introduced in the design of a novel type of MRAC controllers the applicability of which was investigated by simulations for the control of various systems (e.g. [43-46]). Observing the fact that in the classical, Lyapunov function-based solutions as the AID and SLAC controllers the parameter tuning rule obtained from the Lyapunov function has a simple geometric interpretation that is independent of the Lyapunov function itself, the FPI-based solution was combined with the tuning rule of the original solutions used for learning the "exact dynamic parameters" of the controlled system. Alleviated from the burden of necessarily constructing some easily treatable quadratic Lyapunov function, the feedback provided by the FPI-based solution was directly used for parameter tuning. This solution resulted in precise trajectory tracking even in the initial phase of the learning process in which the available approximate model parameters still were very imprecise [47,48]. In the present paper certain novel results are summarized on the further development of the FPI-based approach.

Discussion and Results

The structure of the FPI-based adaptive control

The block scheme of the FPI-based adaptive controller is given in Figure 1 for a 2nd order dynamical system as e.g. a robot [48]. In this case the 2nd time-derivative of the generalized coordinates (joint coordinates). $\ddot{q}$ can be instantaneously set by the control torque or force Q On this basis, in the kinematic block an arbitrary desired joint acceleration $\ddot{q}^{Des}$ can be designed that can drive the tracking error $q^{N}(t)-q(t)$ to 0 if it is realized. In the practice this joint acceleration cannot be realized due to the imprecisions in the dynamic model the CTC controller uses for the calculation of the necessary forces. Therefore, instead introducing this signal into the Approximate Model to calculate the necessary force its deformed version, $\ddot{q}^{Def}$ is introduced into it. The necessary deformation iteratively is produced in the form of a sequence that is initiated by it, i.e. by $\ddot{q}^{Def}$ During one digital control step one step of the iteration can be realized. If there are no special time-delay effects in the system, the contents of the delay boxes in Figure 1 exactly correspond to the cycle time of the controller Δt The "chain of operations" resulting in an observed realized response $\ddot{q}(t)$ for the input $\ddot{q}^{Def}$ mathematically approximately can be considered as a response $\ddot{q}=f\left(\ddot{q}^{Def}\right)$ since –though it depends on q and $\dot{q}$ – only slowly varies in comparison to $\ddot{q}^{Def}$ that quite quickly can be modified. In the Adaptive Deformation Block of Figure 1 a function is used as $\ddot{q}^{Def}(t+\Delta t)=G\left(\ddot{q}^{Def}(t),\ddot{q}(t),\ddot{q}^{Des}(t+\Delta t)\right)$ in which $\ddot{q}(t)=f\left(\ddot{q}^{Def}(t)\right)$ [49]. Since due to the proportional, integral and derivative error feedback terms $\ddot{q}^{Des}$ varies only slowly, we have an approximation as $\ddot{q}^{Def}(t+\Delta t)=F\left(\ddot{q}^{Def}(t)\right)$. Regarding the convergence of this iteration, we have to take it into account that a Banach Space (accidentally denoted by B is a complete, linear, normed metric space. It is a convenient modeling tool that allows the use of simple norm estimations. Its completeness means that each self-convergent or Cauchy sequence has a limit point within the space. A mapping $F:\beta\mapsto\beta$ is contractive if $\exists$ a real number $0\leq K<1$ so that, $\|F(y)-F(x)\|\leq K\|y-x\|\forall x,y\varepsilon\beta$ It is easy to show that the sequence generated by a contractive map as $\{x_{0,}x_1=F(x_{0,}),\ldots,x_{n+1}=F(x_n),\ldots\}$ is a Cauchy sequence: in the norm estimation given in (1) $\forall L\varepsilon$ in high order powers of K occur as $n\to\infty$ therefore $\|x_n+L-x_n\|\to 0$. Due to the completeness of $\beta\exists x_*\varepsilon\beta$ so that $x_n\to x_*$ It is easy to prove that $F(x_*)=x_*$: for an arbitrary element of the sequence x_n according to (2) it holds that $\forall\varepsilon>0\|F(x_*)-x_*\|<\varepsilon$.

$$\|x_{n+L}-x_n\|=\|F(x_{n-1+L})-F(x_{n-1})\|\leq$$

$$K\|x_{n-1+L}-x_{n-1}\|=K\|F(x_{n-2+L})-Fx_{n-2}\|\leq$$

$$K^2\|x_{n-2+L}-x_{n-2}\| \text{ etc} \quad \text{(1a)}$$

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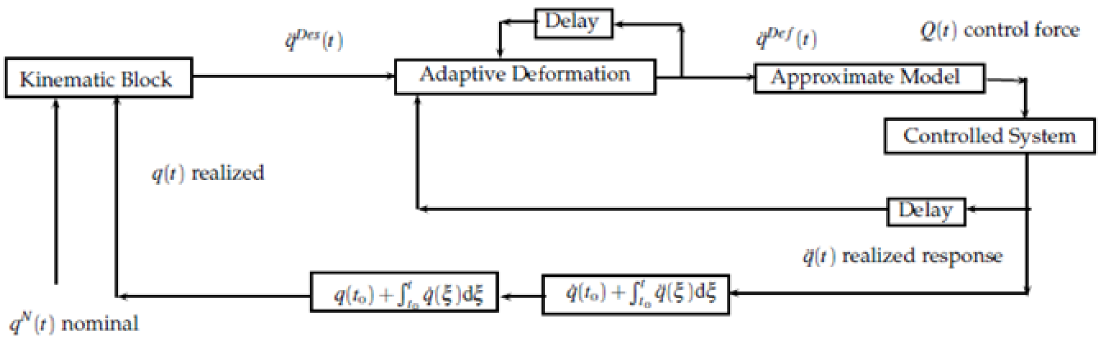

Figure 1: Schematic structure of the "Fixed Point Transformation-based Adaptive Controller" taken from [49].

$$\|F(x_*)-x_*\|=\|F(x_*)-(x_n-x_*)\|=$$
$$\leq\|F(x_*)-F(x_{n-1})\|+\|x_n-x_*\|\leq$$
$$\leq K\|x_*-x_{n-1}\|+\|x_n-x_*\|\to 0 \text{ as } n\to\infty \quad \text{.......... (2a)}$$

Consequently, it is enough to guarantee that the function F(.) is contractive, since in this case the sequence converges to the fixed point of this function if it is so constructed that its fixed point is the solution of the control task.

Construction of the adaptive function

In the original solution in [25] (3) was suggested for the special case $q\varepsilon IR$ with three adaptive parameters K_c, B_c, and A_c.

$$\ddot{q}^{Def}(t+\Delta t)=\left(K_c+\ddot{q}^{Def}(t)\right)\left[1+B_c\tanh\left(A_c\left(f(\ddot{q}^{Def}(t))-\ddot{q}^{Des}(t+\Delta t)\right)\right]-K_c \text{. ..... (3)}$$

Really, when $f\left(\ddot{q}^{Def}(t)\right)-\ddot{q}^{Def}(t+\Delta t)=0$ we just have the solution of the control task and it is obtained that $\ddot{q}^{Def}(t+\Delta t)=\ddot{q}^{Def}(t)=f\left(\ddot{q}_*^{Def}\right)=\ddot{q}^{Def}(t+\Delta t)$, that is the solution is a fixed point. To obtain convergence in the vicinity of the fixed consider the 1st order Taylor series approximation as

$$f\left(\ddot{q}^{Def}(t)\right)=f\left(\ddot{q}^{Def}(t)-\ddot{q}_*^{Def}+\ddot{q}_*^{Def}\right)\approx f\left(\ddot{q}_*^{Def}\right)+\left.\frac{\mathrm{d}f}{\mathrm{d}q}\right|_{\ddot{q}_*^{Def}}\left(\ddot{q}_*^{Def}(t)-\ddot{q}_*^{Def}\right) \text{, (4)}$$

leads to the approximation

$$\ddot{q}^{Def}(t+\Delta t)-\ddot{q}_*^{Def}\approx\left[1+\left(K_c+\ddot{q}^{Def}(t)\right)B_cA_c\left.\frac{\mathrm{d}f}{\mathrm{d}q}\right|_{\ddot{q}_*^{Def}}\right]\left(\ddot{q}_*^{Def}(t)-\ddot{q}_*^{Def}\right) \text{ (5)}$$

On the basis of (5) it is easy to set the adaptive parameters for convergence: by choosing a great parameter $K_c\geq\left|\ddot{q}^{Def}\right|, B_c=\pm 1$ and a small Ac it can be achieved that $\left|\ddot{q}^{Def}(t+\Delta t)-\ddot{q}_*^{Def}\right|<$ therefore the mapping is contractive and the sequence converges to the solution. The speed of convergence depends on setting Ac, and too great value can cause leaving the region of convergence.

For $q\varepsilon IR^n$ (multiple variable systems) a different construction was introduced in [50,51] the convergence properties of which were more lucid than that of the multiple variable variant of (3):

$$\ddot{q}^{Def}(t+\Delta t)\underline{\underline{def}}\left[\zeta\left(A_c\|h(t)\|+x_*\right)-x_*\right]e(t)+\ddot{q}^{Def}(t) \text{ ...(6)}$$

in which the expression $h(t)\underline{\underline{def}}f\left(\ddot{q}^{Def}(t)\right)-\ddot{q}^{Des}(t+\Delta t)$ can be identified as the "response error in time t", and with the Frobenius norm $e(t)\underline{\underline{def}}\frac{h(t)}{\|h(t)\|}$ corresponds to the unit vector that is directed into the direction of the response error, $\zeta: IR\mapsto IR$ is a differentiable contractive map with the attractive fixed point $\zeta(x_*)=x_*$ and $A_c\varepsilon IR$ is an adaptive control parameter. By using the same argumentation with the1st order Taylor series approximation it was shown in [52] that if the real part of each eigenvalue of $\frac{\partial f}{\partial\ddot{q}^{Def}}$ is simultaneously positive or negative, an appropriate A_c parameter can be selected that guarantees convergence.

$$m_1\ddot{q}_1=m_1g-k_1\mathrm{sign}(q_1-L_{01})|q_1-L_{01}|^{\sigma_1}+k_2\mathrm{sign}(q_2-q_1-L_{02})|q_2-q_1-L_{02}|^{\sigma_2}-b_1 \text{ (7)}$$

in which $Q\varepsilon IR^2$ denotes the control force and $q\varepsilon IR^2$ is the array of the generalized coordinates of the controlled system.

The parameter σ_1 , and $\sigma_2>0$ "modulate" the springs' stiffness, the direction of the spring force is calculated by the use of the "signum" function as sign (q_1-L_{01}) while its absolute value is $|q_1-L_{01}|^{\sigma_1}$. The approximate and exact model parameter values are given in Table 1.

Table 1: The system's exact and approximate parameter values.

Parameter	Approximate value	Exact value
Mass of m_1 [kg]	1.5	1.0
Mass of m_2 [kg]	2.6	2.0
Nonlinearity of spring 1 σ_1 [dimless]	1.5	2.0
Nonlinearity of spring 2 σ_2 [dimless]	1.0	2.5

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Spring's stiffness of $k_1\left[\frac{N}{m}\right]$	120.0	100.0
Spring's stiffness of $k_2\left[\frac{N}{m}\right]$	165.0	150.0
Length of L_{01} $[m]$ in zero force case	1.9	2.0
Length of L_{02} $[m]$ in zero force case	3.1	3.0
Viscous friction coefficient b1 $b_1\left[\frac{N-s}{m}\right]$	0.2	0.1
Viscous friction coefficient b2 $b_2\left[\frac{N-s}{m}\right]$	2.5	2.0
Gravitational acceleration g $g\left[\frac{m}{s^2}\right]$	10.0	
Time resolution and cycle time of simulation $\Delta t[s]$	Not Applicable	10-Mar

In the Kinematic Block for the integrated error $e_{\text{int}}(t)\underline{\underline{def}}\int_{t_0}^{t}\left[q^N(\xi)\right]d\xi$ the prescribed "tracking strategy" was $\left(\frac{d}{dt}+\wedge\right)^3 e_{\text{int}}(t)\underline{\underline{=}}0$ that lead to a PID-type feedback $\ddot{q}^{Des}(t)=\ddot{q}^N(t)\wedge^3 e_{\text{int}}(t)+3\wedge^2 e(t)+3\wedge\dot{e}(t)$ that choice guarantees the convergence $q(t)\rightarrow q^N(t)$ as $t\rightarrow\infty$ in the simulations $\wedge=6s^{-1}$ was chosen with $\zeta(x)=\text{atanh}(\tanh(x+D)/2), D=0.3$ in (6). The choice $A_c=-5\times10^{-1}$ resulted in good convergence. The Figure2–6 illustrate the effects of using the adaptive deformation. It is evident that the tracking precision was considerably improved without any chattering effect that are typical in the also simple Sliding Mode / Variable Structure Controllers (e.g. [53,54]. Figure 5 reveals that quite different control forces were applied in the non-adaptive and in the adaptive cases.

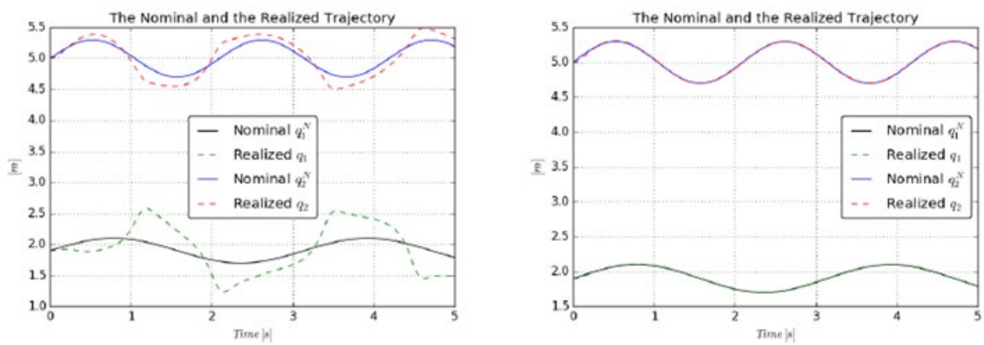

Figure 2: Trajectory tracking without adaptivity (LHS) and with adaptivity (RHS).

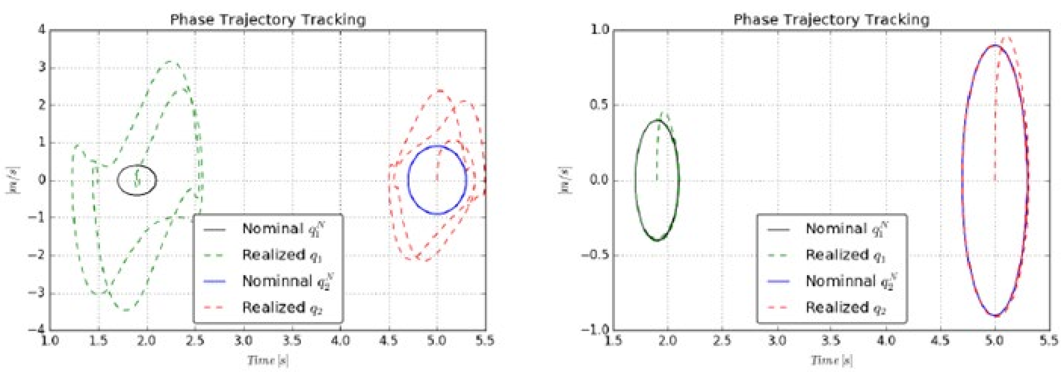

Figure 3: Phase Trajectory tracking without adaptivity (LHS) and with adaptivity (RHS).

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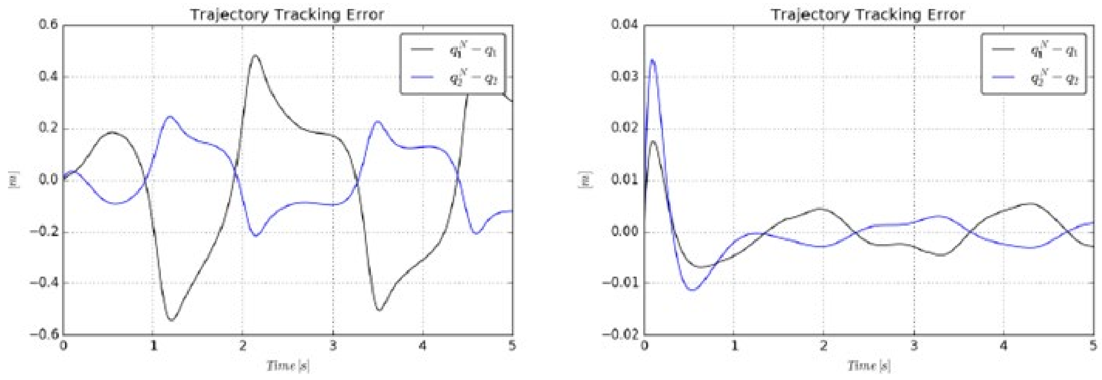

Figure 4: Trajectory tracking error without adaptivity (LHS) and with adaptivity (RHS).

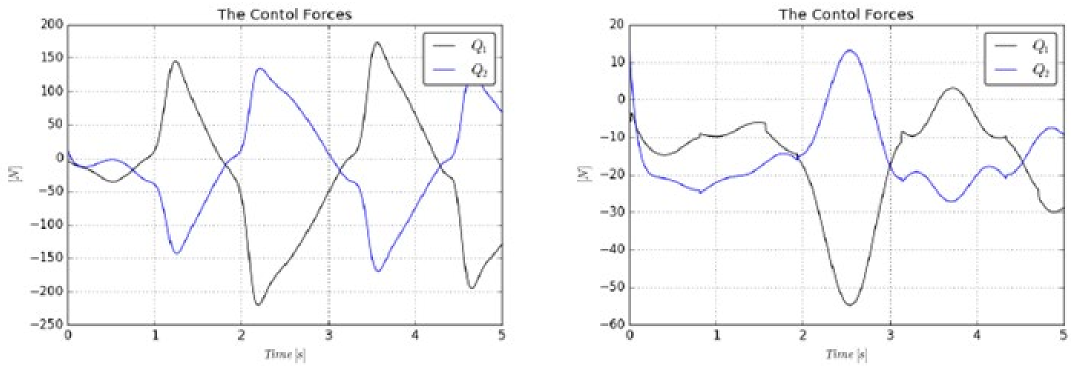

Figure 5: Control force without adaptivity (LHS) and with adaptivity (RHS).

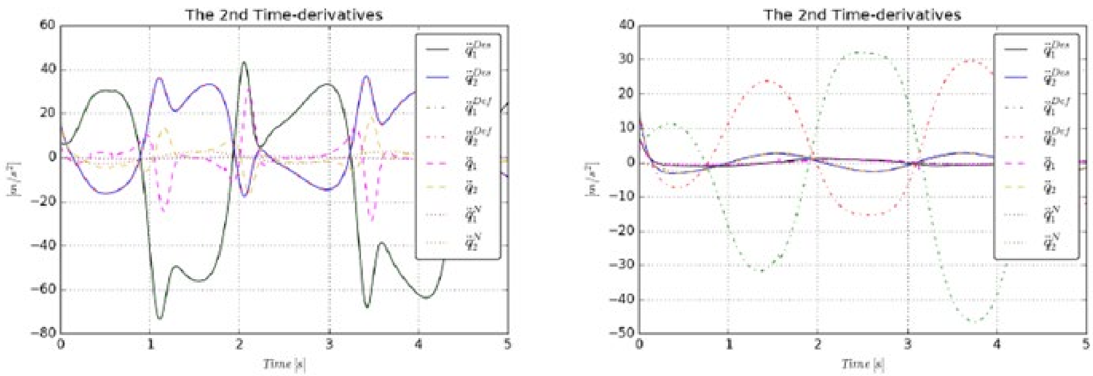

Figure 6: The 2nd time-derivatives without adaptivity (LHS) and with adaptivity (RHS).

The essence of the adaptivity is revealed by Figure 6. In the non-adaptive case considerable PID corrections are added to $\ddot{q}^N(t)$, therefore it considerably differs from $\ddot{q}^{Des}(t)$ that is identical to $\ddot{q}^{Des}(t)$ in the lack of adaptive deformation. However, the difference between the desired and the realized 2nd time-derivatives are quite considerable if no adaptive deformation is applied. In contrast to that, in the adaptive case $\ddot{q}^N(t)$ is in the vicinity of $\ddot{q}^{Des}(t)$ because only small PID corrections are needed if the trajectory tracking is precise. This desired value is very close to the realized 2nd time derivatives that considerably differ from the adaptively deformed value. That is, quite considerable adaptive deformation was needed for precise trajectory tracking due to the great modeling errors.

Further Possible Applications and Development

The applicability of the FPI-based adaptive control design methodology was investigated in various potential fields of application. In 2012 in [55] an adaptive emission control of

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freeway traffic was suggested by the use of the quasistationary solutions of an approximate hydrodynamic traffic model. In [56] an FPI-based adaptive control problem of relative order 4 was investigated. In [57] FPI-based control of the Hodgkin-Huxley Neuron was considered. In [58] the possible regulation of Propofol administration through wavelet-based FPI control in anaesthesia control was investigated.

In [59] the application of the FPI-based control in treating patients suffering from "Type 1 Diabetes Mellitus" was studied. The simplicity of the FPI-based method opened new prospects in the possible design of adaptive optimal controllers. In [60] the contradiction between the various requirements in OC was resolved in the case of underactuated mechanical systems in the following manner: instead constructing a "cost function contribution" to each state variable the motion of which needed control, consecutive time slots were introduced within which only one of the state variables was controlled with FPI-based adaptation. (The different sections may correspond to different relative order control tasks.) In [61] it was pointed out that the FPI-based control can be easily combined with the mathematical framework of the "Receding Horizon Controllers" (RHC) (e.g. [62]). (A combination with the Lyapunov function-based adaptive approach would be far less plausible and simple.) In [49] the applicability of this approach was introduced into the control of systems with time-delay. The possibility of fractional order kinematic trajectory tracking prescription in the FPI-based adaptive control was studied, too [63].

In [64] its applicability was investigated in treating angiogenic tumors. In [65,66] further simplification of the adaptive RHC control was considered in which the reduced gradient algorithm was replace by a FPI

in finding the zero gradient of the "Auxiliary Function" of the problem. In [67] the applicability of the method was experimentally verified in the adaptive control of a pulse-width modulation driven brushless DC motor that did not have satisfactory documentation (FIT0441 Brushless DC Motor with Encoder and Driver) and was braked by external forces simply by periodically grabbing the rotating shaft by one's two fingers. The solution was based on a simple Arduino UNO microcontroller with embedding the adaptive function defined in (3) into the motor's control algorithm. In spite of using 2[nd] time-derivatives in the feedback no special noise filtering was applied. The measured and computed data was visualized by a common laptop. As it can be seen in Figure 7, the rotational speed was kept at almost constant (in spite of the very noisy measurement data), and the adaptive deformation and the control signal were well adapted to the external braking forces in harmony with the simulation results belonging to the "Illustrative Example" in subsection 2.3.

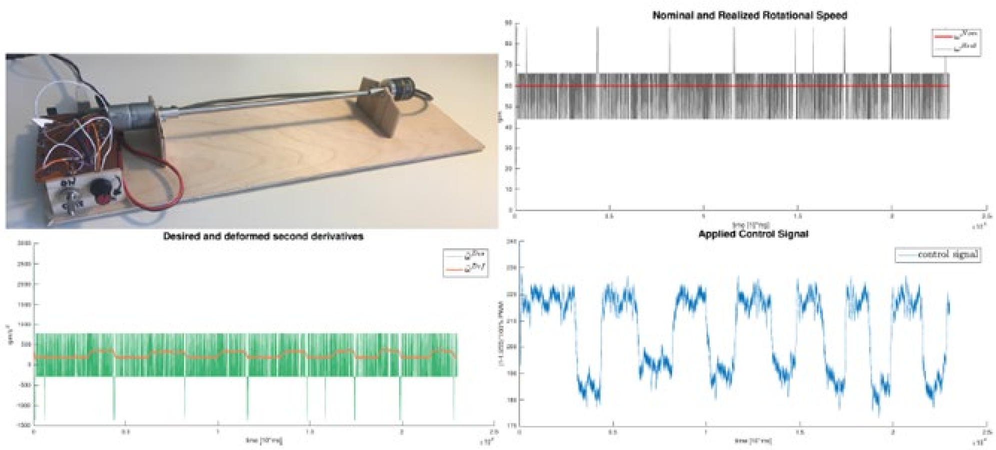

Figure 7: The measured and computed data was visualized by a common laptop.

Figure 7: The experimental setup used for the verification of the FPI-based adaptive control in the case of a pulse-width modulated brushless electric DC motor; The nominal and the realized rotational speed (the average of the whole data set was 59:9383rpm, the nominal constant value was 60rpm); The "Desired" and adaptively "Deformed" 2[nd] timederivatives of the rotational speed; The control signal (from [67], courtesy of Tamás Faitli) In [68] the novel adaptive control approach was considered from the side of the Lyapunov function-based technique and it was found that it can be interpreted as a novel methodology that is able to drive the Lyapunov function near zero and keeping it in its vicinity afterwards. On this basis a new MRAC controller design was suggested in [69] that has similarity with the idea of the "Backstepping Controller" [70,71].

Conclusion

The FPI-based adaptive control approach was introduced at the Óbuda University with the aim of evading the mathematical difficulties and restrictions, furthermore the information need related to the traditional Lyapunov function-based design. Its

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main point was the transformation of the control task into a fixed-point problem that was iteratively solved on the firm mathematical basis of Banach's fixed point theorem. In the center of the new approach, instead of the requirement of global stability, as the primary design intent, precise realization of a kinematically (kinetically) prescribed tracking error relaxation was placed. In contrast to the traditional soft computing approaches as fuzzy, neural network and neuro-fuzzy solutions that normally apply huge structures with ample number of the parameters of the universal approximators of the continuous multiple variable functions on the basis of Kolmogorov's approximation theorem (e.g.

[72-74]) this approach has only a few independent adaptive parameters that can be easily set and one of them can be tuned for maintaining the convergence of the control algorithm. It was shown that the simplicity of this approach allows its combination with more "traditional" approaches as that learning the exact model parameters of the controlled system and at various levels of the optimal controllers as the RFC control. On the basis of ample simulation investigations, it can be stated that the suggested approach has wide area of potential applications (in the control of mechanical devices, in life sciences, traffic control, etc.) where the presence of essential nonlinearities, the lack of precise and complete system models, and limited possibilities for obtaining information on the controlled system's state are present as main difficulties. It seems to be expedient to invest more efforts into experimental investigations.

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